Experimentation and Evaluation of Tyre Pyrolysis Oil

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Bachelor of Technology in Mechanical Engineering

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CERTIFICATE

This is to certify that the thesis entitled, "Experimentation and Evaluation of Tyre Pyrolysis Oil" submitted by Shubharanshu Shekhar Mahapatra in partial fulfillment of the requirements for the award of Bachelor of Technology in Mechanical Engineering at the National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/ Institute for the award of any Degree or Diploma.

Date: 09-05-2014

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ABSTRACT

Scrap tyre consists of organic matter that is often disposed illegally in open lands, ultimately causing an environmental problem. Pyrolysis is considered as a useful technique for recycling of scrap tyres by using which liquid, gases, carbon black and steel wires are obtained. The difficulty in using Tyre Pyrolysis Oil (TPO) as an energy source is its complex chemical composition. The following report discusses about how the oil can be effectively utilized by separating it according to composition using the process of fractional distillation. From 1.5 Litre of TPO 350 ml of distilled oil is obtained in the temperature range of 200-270 ^{0}C which is blended with diesel to be used as high grade fuel to run a DI 4 stroke single cylinder diesel engine. The TPO left in the flask after distillation is found to have high viscosity, high fire point and high pour point; as a result of which it is utility is found in being used as a base for manufacture of lubricants. By employing such techniques the commercial value of TPO is increased and also better results were obtained. With increase in utility of TPO it is expected that more such manufacturing plants will come up. This will help to recycle more percentage of waste tyres from among the 1 billion scrap tyres generated each year around the world.

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NOMENCLATURE

BSEC – Brake specific Energy Consumption

bTDC – Before Top Dead Center

BTE – Brake Thermal Efficiency

CA – Crank Angle

FTIR - Fourier Transform Infrared Spectroscopy

GC-MS – Gas Chromatography Mass Spectroscopy

LFPO – Light Fraction Pyrolysis Oil

NOx – Oxides of Nitrogen

P – Instantaneous Pressure

TPO – Tyre Pyrolysis Oil

V – Instantaneous Volume

$\dot{Q}$ - Heat Release Rate

xxLFPO – xx percent of LFPO in 1 L blend.

γ - Ratio of specific heat

θ – Measure of Crank Angle in Degree

Chapter 1

Introduction

INTRODUCTION

1.1 Waste Products and their Classification

Wastes are materials for which a user doesn't find any primary use and wants to dispose the product. On basis of their effects on Human health and Environment, wastes are classified into 7 different categories, as represented in Figure 1.1 [1].

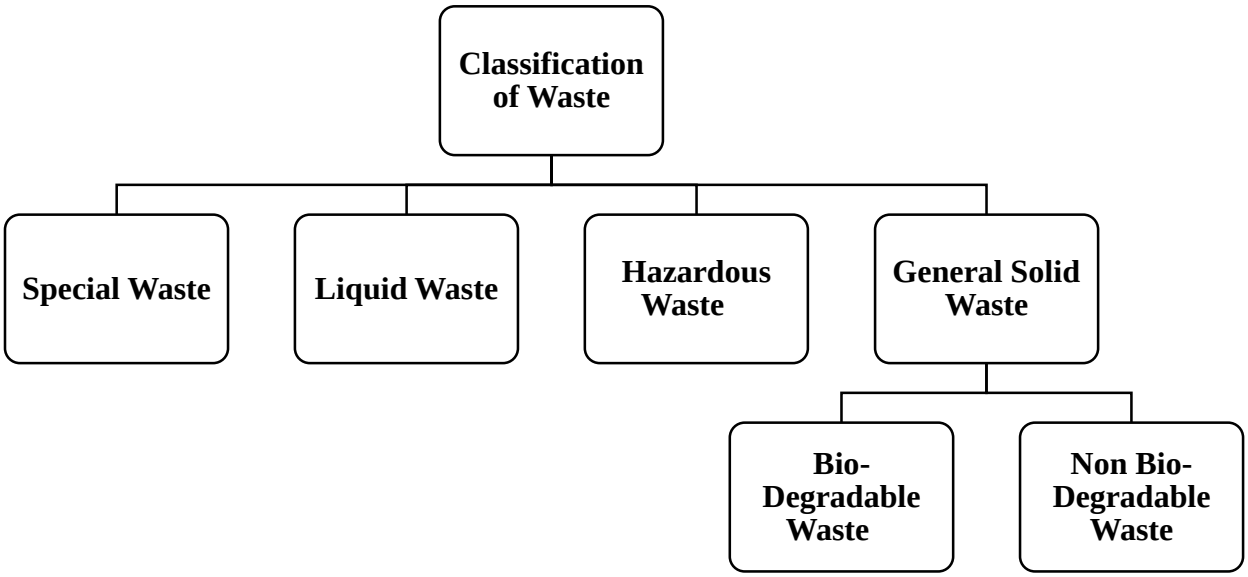

Figure 2.1 Classification of Wastes

1.1.1 Special Waste

'Special Waste' are a category of wastes that have unique regulatory requirements. These should be managed in a streamlined way to minimize harm to the environment and human health. These can be any of the following types:

- Clinical and related waste
- Asbestos Waste
- Waste Tyres

1.1.2 Liquid Waste

For a waste to be classified as a liquid waste it must have the following characteristics:

- Has an angle of repose less than 5 degrees above horizontal
- Becomes free-flowing at below 60 ^{0}C or when it is transported
- Is generally not capable of being picked up by a spade or shovel

1.1.3 Hazardous Waste

Wastes exhibiting characteristics like toxicity, corrosiveness, flammability and reactivity are categorized under hazardous waste. European Pollution Authority (EPA) has classified hazardous waste as:

- Containers that previously contained goods that are deemed dangerous for transportation, from which residues have not been washed or vacuumed out.
- Coal tar or pitch waste.
- Lead acid or nickel-cadmium batteries.
- Lead paint waste from residential and educational areas
- Nuclear waste.

1.1.4 General Solid Waste

General solid waste are grouped into two categories

1. Bio-degradable
2. Non Bio-degradable

Bio-degradable waste products: This is a type of waste that can be broken down by microbes or other living organism in a reasonable amount of time. Ex: Wood, Vegetable waste.

Non Bio-degradable products: These are products which either cannot be broken down by microbes or it takes a long duration for them to do so. Ex Plastic

1.2 Waste Tyres

Tyre consists of vulcanized rubbers (including styrene butadiene (SBR), natural rubber (NR) and polybutadiene (BR)), carbon black, steel, textile cord and small amount of other additives [2]. They are produced in huge volumes and have a low lifespan. Durability of waste tyres is especially low in India due to poor road conditions and harsh climate. Owing to large number of vehicles and

low lifespan of tyres it is estimated that 190 million tons of waste tyres are being generated each year in India alone [2].

1.3 Methods of Waste Tyre Recycling

Waste tyres are recycled in different ways which are:

1. Retreading
2. Landfills
3. Using as construction Materials
4. Incarnations
5. Tyre Derived Fuel

Retread is a manufacturing process designed to extend the lifespan of worn out tyres. The old tread is removed and a new tread is applied to the bare casing using specialized tools. This procedure is regularly carried out in airplane tyres as they are worn out very frequently and the necessity for them to be in good condition. On an average 4.5 gallons of oil is saved through this process compared to manufacture of a new tyre. In case of commercial vehicles, the savings can go upto 12.5 gallons of oil.

Land filling is the most common way of disposing waste tyres, accounting up to 53% of the total waste tyre generated. But it has a serious impact on land usage, fertility of land and is a potential hazard as it is prone to fires. Tyres are very difficult to extinguish when they catch fire. Citing this many countries have banned this form of disposal of waste tires.

Incineration and TDF are two waste to energy technologies that are available for the treatment of waste tyres. In incineration, energy recovery systems are used to recover the energy. TDF or tyre derived fuel the energy remains in a liquid form that can be used in combustors, IC engine etc.

The importance of finding use for waste tyres can be deduced from the fact that we produce nearly 1 billion waste tyres each year. The composition of passenger vehicle tyres is approximately 85% carbon, 10–15% fabric materials and 0.9–1.25% sulfur. The typical percentages of the rubber mix are 55% synthetic rubber (polybutadiene) and 45% natural rubber (latex) in passenger vehicle tyres. Thus, the abundant organic matter (OM) contents of tyres can be converted into useful products for energy sources. Pyrolysis is one of the methods to derive alternative fuels, in which

organic substances are converted into useful energy. One of the methods to derive alternative fuels is pyrolysis in which waste substances are converted into useful energy. Pyrolysis is a thermo chemical conversion process in which an irreversible chemical change is caused by the action of heat in absence of oxygen. This process yields value added products such as fuels or chemicals in the form of solid, liquid or gas. Without oxygen, the process splits the chemical bonds and leaves the energy stored in the organic substance. The main advantages of pyrolysis include compactness, simple equipment, low pressure operation, negligible waste product and high energy conversion efficiency of the order of 83%.

The oil obtained after pyrolysis is termed as Tyre Pyrolysis Oil (TPO). Pyrolysis of tyres yield liquid fuel, gases, carbon black and steel wires. Tyre Pyrolysis Oil can be directly used as fuel in Combustors and IC engines. Although using in such systems is effective, the complex composition poses huge challenges for use of TPO as a combustion fuel. Presence of Phenolic, Quinoline and PAH compounds leads to high emissions and high maintenance cost.

To address the drawbacks of using TPO, in this investigation vaccum distillation technique was used. TPO was distilled and separated in temperature ranges of 170 -190 ^{0}C, 190 -210 ^{0}C, 210 – 230 ^{0}C and 230 -270 ^{0}C. Not only this technique separated the TPO according to its composition, but also made it a cleaner fuel by removing all the sulfur content present in TPO. Test showed that the distillate had no sulfur content. Instead of wasting the high boiling point substances that remained in the flask, it has been tried to be used as base stock for manufacturing lubricants.

1.4 Motivation

The aim of this research work is to make TPO a profitable fuel having varied usage. Statistics show that only 25% of waste tyre are recycled to generate TPO. One of the major cause is high time of recovery of invested funds and other cause is the limited use of TPO. This led to the development of fuel processing technique that diversifies the field of use of TPO.

TPO by distillation is a very important procedure that is often looked upon. If TPO is directly used as fuel, the presence of PAHs and aromatic compounds release many harmful anthropogenic gases into the atmosphere. There is sulfur content present in it, which means that it is almost impossible for the fuel to pass stringent emission standards when used in IC engines in future. By distilling it we obtain a very clean fuel which is completely free from sulfur and PAHs. The added advantage

gained is that the present fuel doesn't require oxygen rich environment for combustion. This prevents the use of highly oxygenated fuels which give high NOx emissions. Lubricants do not undergo combustion and seldom come in direct human exposure. So the risk of releasing harmful toxic gases is greatly reduced compared to all other methods of disposing scrap tyres. Thus the remains of the distillation can be used to manufacture low grade lubricants.

The research work was carried out to make TPO an environmental friendly fuel and also increase its commercial value.

Chapter 2

Literature Review

LITERATURE REVIEW

Tyre Pyrolysis Oil is one of the product of pyrolysis of tyres. For the past 20 years it is being used as a fuel. Researchers have successfully blended TPO with diesel to run CI engines. Researchers have also characterized the fuel to understand the constituents present in it. Their research and findings are listed below.

2.1 Tyre Pyrolysis Oil

Bhatt et al [2] have studied the suitability of TPO as a fuel to be used in IC engines. According to their research about 190 million tonnes of tyres are produced each year in India alone. They analyzed the properties of TPO and concluded that it can be used as fuel for industrial furnaces and boilers in power plants due to their high calorific value, low ash and sulphur content. But TPO has higher density, kinematic viscosity and lower cetane value compared to that of diesel. This limits its use as a fuel in IC engines. They proposed to use TPO blended with diesel fuel in various proportions by volume keeping the blend quality under permissible limits.

During early years of work, Murena et al [3] did a study on the product produced by hydrogenative pyrolysis of waste tyres. They investigated the temperature ranges between which solid phase and liquid phase products are formed. In order to maximize gaseous products, the temperature of the plant was proposed to be kept at 400^0C. They studied the compunds present in both phases and also the residual char left after pyrolysis. GC-MS analysis of TPO was extensively done by Islam et al [4]. Their report revealed that fixed bed fire-tube heating pyrolysis is a viable option for producing the fuel. The TPO yields from such a plant has fuel properties like diesel, viscosity and hydrogen content similar to that of diesel. For the present work TPO produced from such a setup was taken and the properties were verified.

One of the major problems of TPO is its sulphur content. Before it can be used as a fuel the sulphur content has to be minimized. Curmali et al [5] reported different methods of desulphurization. They found that pyrolysis done at 500^0C yielded low sulphur TPO. Their research revealed, treating TPO with CaO, $Ca(OH)_2$ derivatives, formic acid - H_2O_2 or acetic acid – H_2O_2 was effective for desulphurization of TPO. In the present report, slow distillation of TPO was found effective in desulphurization of TPO.

2.2 TPO as a Fuel in IC Engines

Williams et al [6] studied the compounds present in TPO along with its combustion in a ceramic lined furnace. Their investigation revealed that TPO has PAH in high concentrations. They found high SO_2 and NO_x emissions. To avoid PAH, they proposed combustion under excess oxygen conditions. Sharma and Murugan [7] created an oxygen rich environment by blending TPO with an oxygenated fuel i.e Jatropha Methyl Ester. They reported NOx and SO_2 emissions comparable to that of diesel when used in an IC engine. S. Murugan et al found that TPO when blended with diesel showed anomalous combustion and performance characteristics. They reported that TPO when blended with diesel in ratio of 30 - 40 % by volume, gives better combustion and performance than all other blends.

Ramaswamy et al [8], in their research work tested that CI engines can run upto 90% distilled TPO blend, above which the engine fails becomes dysfunctional. They carried out distillation $<200^0$C which the kerosene range. Findings of their research showed higher smoke, HC emissions but lower NOx emissions compared to that of diesel when used to run a DI diesel engine.

Studies carried out on aromatic fuel have shown that they give lower performance and higher emission compared to that of diesel fuel. They are low cetane fuel with longer ignition delay. In a special case, when aromatic compounds are connected with long chain alkanes, have good cetane numbers compared to other aromatic compounds [9]. Pioneering work carried out by Kidoguchi et al [10] provide effect of cetane number and aromatic content of a fuel on combustion and emission characteristics of an IC engine. They have reported that:

- Keeping aromatic content constant, decreasing the cetane number increases NOx emissions and decreases particulate emissions.
- With increase in aromatic content both NOx and particulate emission increases.

Other surveys included patent search on lubricating oil and distillation products of crude oil. The present work relates TPO distillation products with that of distillation products of crude oil. From these surveys it was concluded that many have worked on characteristics on TPO and it being used as a fuel. But the focus has not been on studying the combustion process and also on improving TPO as a source from which valuable products can be derived

Chapter 3

PROPERTIES AND CHARACTERIZATION

PROPERTIES AND CHARACTERIZATION

3.1 General

Pyrolysis is a thermo-chemical conversion process in which an irreversible chemical change caused by the action of heat in absence of oxygen [11]. Tyre is composed of 85% Carbon, 10 – 15% fabric material and 0.9-1.25% Sulphur [2]. Pyrolysis of tyres yeilds products like [12] :

1. Fuel Oil – (40 – 45 %)
2. Carbon Black – (30 – 35%)
3. Steel Wire – (3 – 5%)
4. Non Condensable Gases – (8 – 10%)
5. Moisture – (3 - 5%)

The Tyre Pyrolysis Oil obtained is a blackish liquid with pungent odour. In an unrefined state it contains small particulate carbon suspended in the liquid medium.

3.2 Production of Tyre Pyrolysis Oil

Tyre Pyrolysis Oil used for this research work was obtained from a pilot plant located in the city of Rourkela. The schematic illustration of the plant is given in Figure 3.1. The plant is a rotary type, pyrolysis reactor. The dimensions of the reactor is approximately 6.6 m in length, diameter is 2.8 m and has a capacity of 10 tons per batch. The reactor is rotated with the help of electrical motors. Initially it is fired up with waste wood and then coal is used to keep it burning. In the plant, shredded tyres are fed into the reactor. The front end of the reactor has a door with fasteners and can be opened or closed by unlocking or locking the fasteners respectively. The other end of the reactor is connected to a sealing element and a flexible connection. The volatile vapour which is formed during pyrolysis pass through the oil separator where heavy oil is separated by gravity and collected in an oil tank. A damper is provided at the outlet of the oil separator that connects to a series of water cooled pipes. The volatile gases pass through these condenser pipes where the light fractions are converted into liquid. A cooling tower is used to bring the temperature of coolant near atmospheric temperature. The whole setup and its accessories are operated by motor and pumps with the help of a control panel. The initial temperature at which volatile vapour evolve is 160^0C. During the process, carbon black and steel wires are also generated.

3.3 Analysis of Tyre Pyrolysis Oil

The Fourier Transform Infrared Spectroscopy (FTIR) offers a quantitative and qualitative analysis for organic and inorganic samples. The spectra produce a profile of the sample a distinctive molecular fingerprint that can be used to screen and scan samples for many different components. It identifies chemical bonds in a molecule by producing an infrared absorption spectrum. The FTIR is an effective analytical instrument for detecting functional groups and characterizing covalent bonding formation. The FTIR test was carried out with Perkin Elmer Spectrum ONE equipment which has a scan range of 450-4000 cm^{-1} with a resolution of 1.0 cm^{-1}. The FTIR analysis of TPO revels that, the functional group present are almost aromatics and hydrocarbons. Table 2.1 gives the FTIR analysis of TPO. The compounds of light tyre pyrolysis oil are alkanes, alkenes, aromatic compounds, but in case of diesel the compounds are alkanes, alkenes, alcohol, nitrate, chloride and bromide.

Table 2.1 FTIR Analysis of TPO

Tyre Pyrolysis Oil					
Wave number(cm^{-1})	**Bonds**	**Class of compounds**	**Frequency range (cm^{-1})**	**Bonds**	**Class of compounds**
2921.33	C-H, Stretch	Alkanes	3095-3005	C=C stretching	Alkenes
2812.72	C-H, Stretch	Alkanes	3000-2800	C-H stretching	Alkanes
1605.47	C=C, C=N, Stretch	Alkenes, Amide	1680-1620	C=C stretching	Alkenes
1461.19	O-H, Bending	Alcohol	1600-1525	Carbon-carbon stretching	Aromatic compounds
1376.55	Nitrate	Nitrate	1520-1220	C-H bending	Alkanes
722.05	C- Cl	Chloride	1035-830	C=C stretching	Alkenes

3.4 GC-MS Analysis of TPO

The Gas chromatography ("GC") and mass spectrometry ("MS") make an effective combination for chemical analysis. Gas chromatography (GC) is used to separate mixtures into individual components using a temperature-controlled capillary column. Smaller molecules with lower boiling points are travel down the column more quickly than larger molecules with higher boiling point. The mass spectrometry (MS) is used to identify the various components from their mass spectra. Each compound has a unique or near unique mass spectrum that can be compared with mass spectral databases and thus identified. Through use of standards, quantification is also possible. The compounds detected in TPO by GC-MS analysis is given in Table 2.2.

Table 2.2 GC-MS Analysis of major compounds present in TPO

GC-MS Analysis of TPO							
R. time	**Area (%)**	**Name of compound**	**Molecular formula**	**R. time**	**Area (%)**	**Name of compound**	**Molecular formula**
3.290	4.85	p-Xylene Benzene, 1,3-dimethyl-	C_8H_{10} or $C_6H_4(CH_3)_2$, $C_{10}H_{14}$	3.065	0.98	1-Ethyl-Metylcyclohexane	C_9H_{18}
4.859	6.24	Benzene,	C_9H_{12}	3.359	1.06	Propyl cyclohexane	$C_6H_{11}CH_2$- CH_2CH_3
5.236	2.17	Benzonitrile	C_6H_5CN	3.782	1.04	M-Ethyl methyl benzene	C_9H_{12}
5.962	15.24	Benzene, 1,2,3,4-tetramethyl, o-Cymene	$C_{20}H_{26}O$, $CH_3C_6H_4CH(CH_3)_2$	4.274	3.51	Decane	$C_{10}H_{22}$
6.035	5.19	D-Limonene	C10H16	5.822	2.14	n-Undecane	$C_{11}H_{24}$
10.45	2.19	1H-Indene, 2,3-dihydro-1,1,5-trimethyl-	C_9H_8	7.356	2.71	Dodecane	$CH_3(CH_2)_{10}CH_3$
12.207	3.77	Naphthalene, 2,7-dimethyl	$C_{10}H_8$, $C_{10}H_6(CH_3)_2$	15.959	3.38	n-Hexadecane	CH_3 $(CH_2)_{14}$ CH_3

12.411	4.58	Quinoline, 4,8-dimethyl	C_9H_7N, $C_{11}H_{18}$	17.885	2.57	Octadecane	$CH_3(CH_2)_{16}CH_3$
13.587	4.65	Naphthalene, 2,3,6-trimethyl	$C_{10}H_8$, $C_9H_{12}O$	19.648	1.61	Octacosane	$C_{28}H_{58}$
19.585	2.68	Heptadecanenitrile, Octadecanenitrile, Hexadecanenitrile	$C_{17}H_{33}N$. $C_{18}H_{35}N$, $C_{16}H_{31}N$	20.476	1.35	Tetracosane	$H(CH_2)_{24}H$

From Table 2.2 it is found that the major compounds present in the LFPO are p-Xylene Benzene, 1,3-dimethyl, Benzene, 1-ethyl-4-methyl, D-Limonene, 1H-Indene, 2,3-dihydro-1,1,5-trimethyl-, Naphthalene, 2,7-dimethyl, Quinoline, 4,8-dimethyl, Naphthalene, 2,3,6-trimethyl, Heptadecanenitrile, Octadecanenitrile and Hexadecanenitrile. In diesel fuel the compounds are 1-Ethyl-Metylcyclohexane, Propyl cyclohexane, M-Ethyl methyl benzene, Decane, n-Undecane, Dodecane, n-Hexadecane, Octadecane, Octacosane and Tetracosane. The benzene, Hexadecane, Octadecane, 1-ethyl-4-methyl compound are commonly available in both fuels.

Chapter 4

Experimental Setup and Methodology

4. EXPERIMENTAL SETUP AND METHODOLOGY

4.1 General

All the experimental setups and instruments used will be discussed in this section. The procedure followed to grade the oil will be conversed about. All the setups are mentioned in chronological order of their usage. The significance of combustion, performance and emission parameters calculated will also be elaborated.

4.2 Distillation Setup

Distillation is a process of purifying liquid based on their different boiling points. An illustration of the setup used for carrying out this research work is shown in Figure 4.1.

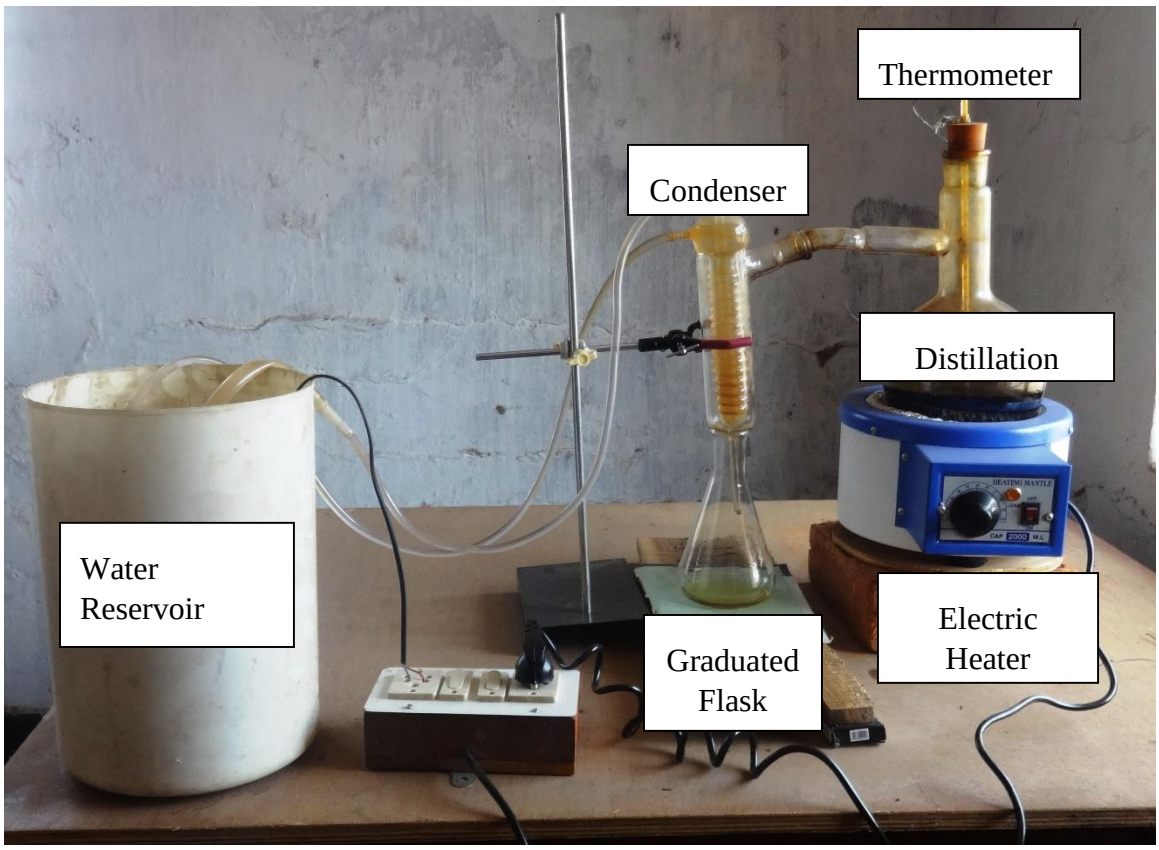

Figure 4.1 Distillation Setup

A constant heat supply was provided to the distillation flask by the use of an electric heater. The heater had a control knob using which the rate of heating can be adjusted. Temperature was

measured using a thermometer which had a range from 0^0C to 360^0C. The vaporized liquid passes through a water cooled condenser and collected in a flask. The process of fractionating the liquid according to temperature was done manually. A pump was used to maintain constant flow of water into the condenser.

A constant heat supply was provided to the distillation flask by the use of an electric heater. The heater had a control knob using which the rate of heating can be adjusted. Temperature was measured using a mercury thermometer which had a range from 0^0C to 360^0C. The vaporized liquid passes through a water cooled condenser and collected in a flask. The process of fractionating the liquid according to temperature was done manually. A pump was used to maintain constant flow of water into the condenser.

4.3 Engine Experimental Setup

For this experimental work a single cylinder, 4 stroke, air cooled, DI diesel engine was used. The specification of the engine are given in Table 4.1.

Table 4.1 Details of Test Engine

Make/model	**Kirloskar TAF 1**
Brake power (kW)	4.4
Rated speed (rpm)	1500
Bore (mm)	87.5
Piston type	Bowl-in-piston
Compression ratio	17.5:1
Nozzle opening pressure (bar)	200
Injection type	23 BTDC
Cooling System	Air cooling

The engine has stroke length of 87.5mm and piston diameter of 55mm. It piston is bowl in type piston. An internal view of the engine is given in Figure 4.2.

Figure 4.2 Engine Experimental Setup

An electrical dynamometer connected to a resistive load bank, was used to load the engine. The fuel measuring system consisted of a burette fitted with two optical proximity sensors, one at the top and other at the bottom. As the fuel passed through the higher level optical sensor, the sensor gave a signal to the data acquisition system (DAS) to start the counter. Once the fuel reached the lower level sensor, the sensor gave a signal to the DAS to stop the counter time and refill the burette. From this, the time taken for the consumption of fuel for a fixed volume was calculated. A differential pressure sensor fitted in the air box measures the air consumption. The differential pressure sensor was used to measure the pressure difference between the orifice plates. The

differential pressure sensor also gave a proportional voltage output with respect to the difference in pressure. A schematic representation of the system is given in Figure 4.3

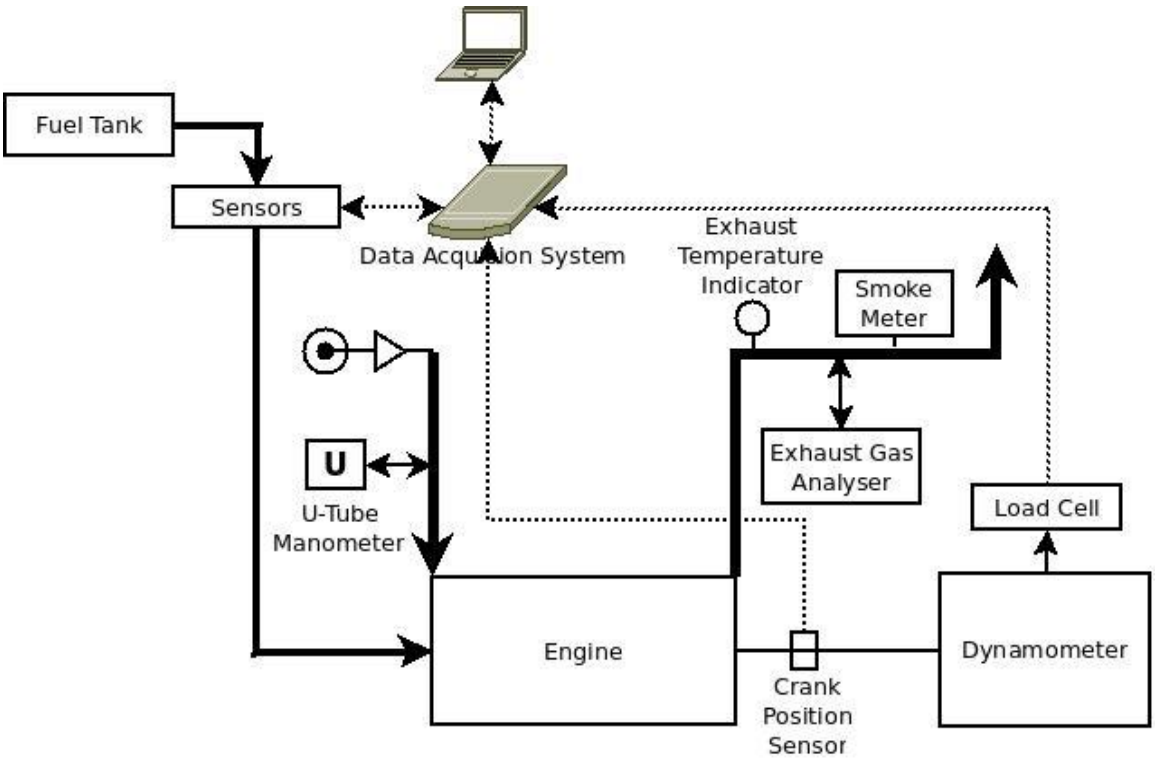

Figure 4.3 Schematic Representation of Test Engine

4.4 Data collection for performance parameters

4.4.1 Brake thermal efficiency (BTE)

To determine the brake thermal efficiency of the engine, three input parameters were measured:

1. Time taken for 20 cc of fuel consumption
2. Lower heating value of the test fuel
3. Fuel density.

Brake Thermal Efficiency (BTE) can be calculated as:

BTE = (brake power x 3600 x 100/ (volumetric fuel flow rate per hour x fuel density x calorific value of fuel)). (4.1)

4.4.2 Brake specific Energy consumption (BSEC)

To determine the brake specific fuel consumption the formula used is:

BSEC = (Calorific value of fuel x volumetric fuel flow rate per hour x fuel density/brake power) (4.2)

The BTE and BSEC were displayed in the form of excel sheet generated by the data acquisition system software (Engine test express) using the above mentioned expressions.

4.5 Engine Parameters measurement Devices

4.5.1 Piezo electric transducer

To acquire important combustion parameters, such as ignition delay, combustion duration etc., the cylinder pressure and crank angle values are necessary. The cylinder gas pressure was measured using a Kistler piezo-electric transducer (model 5395A) in conjunction with a Kistler charge amplifier as shown in Figure 4.4.

Figure. 4.4 Photographic view of Kistler pressure transducer

The cylinder gas pressure data was recorded as the average of 20 cycles of data, with a resolution of 0.5°CA using a data acquisition system. These data were averaged over that period, recorded in excel sheet and parameters like pressure vs crank angle values, the peak pressure, occurrence of the peak pressure, maximum rate of pressure rise, and heat release rate were calculated.

The TDC marker (Kistler model 5015A1000) was placed near the engine flywheel. At the TDC position, a small metallic deflector was fitted. The setup was aligned in such a way that the sensor gives out a square wave output, exactly when the piston is at the TDC.

4.5.2 Proximity Sensors

Proximity Sensors were used to measure fuel flow rate. It measures the time gap between 20 ml of fuel consumed. Two sensors are placed at the ends of a graduated tube. It notes the time when the fuel column passes through each of the sensors. After the column has passed the lower sensor the system is reset to take the next set of data. All the readings are sent to the Data Acquisition System.

4.5.3 Analog to Digital Converter

The analog signals from the sensors were fed into the Analog to Digital Converter (ADC) and then passed to the display unit, through the data acquisition cord and microcontroller. The analog signals were converted into digital using the ADC, which was finally fed to a display unit through the data acquisition system. Using the data acquisition system graphical analysis, evaluating the differential equation, computing the mathematical expression, display, control and recording were done for various engine operating parameters, like instantaneous pressure, crank angle, temperature, and the heat release rate. From this other combustion parameters such as ignition delay, cumulative heat release rate, mass fraction burned and combustion duration were computed. A computer was used to process and store the data during investigation.

4.5.4 Gas Analyzer

The exhaust gas sample was analysed by a 5 Gas analyzer (Make: AVL India, Model: 444) fitted with a DiGas sampler, conforming to ARAI certification: ARAI/TA(4G-RV)/AVL/DiGas 444/0910-12. The principle for measuring the CO, HC, CO_2 emissions was the NDIR (non-dispersive infrared), and for the NO and O_2, it was electrochemical. The CO, CO_2, O_2 emissions

were measured in volume percentage, while the total unburnt hydrocarbon TUHC was measured in ppm (vol.) of n-hexane equivalent, and the NO emission was measured in ppm (vol.) during each run of the engine operation.

4.5.5 Smoke Analyzer

The smoke emission was measured by a partial-flow sampling AVL (Austria) 437 diesel smoke meter, certified by ARAI, Pune, India, as per ARAI/TA(SM-RV)/AVL/437/1011-02. It is based on loss of light intensity due to smoke generated and reported as %age opacity based on beer lambert's law.

4.6 Research Methodology

The distillation was carried out during night time scheduled 5 pm – 11 pm. The procedure was carried out in two phases.

In the first phase the following temperature ranges were chosen:

1. 190 - 210 ^{0}C
2. 210 - 230 ^{0}C
3. 230 - 250 ^{0}C

These were done on the basis of quantity of distillate obtained, which was negligible below the specified range. Study was done on the fuel properties of the three distillates obtained.

In the second phase the temperature range were based on crude oil distillation ranges. The three ranges which were chosen are:

1. 140 - 200 ^{0}C (Below 140 no liquid was obtained)
2. 200 - 270 ^{0}C
3. Above 270

These ranges represent kerosene range, diesel range and lubricating oil range respectively. Each cycle was carried out for 6 hours in which 1.5 litres (capacity of distillation flask) of TPO was distilled. The fractionating of distillate was done manually by observing the temperature in the thermometer. A constant heat supply of 40 watt was supplied continuously to the distillation flask using an electric heater. Temperatures were checked manually and the fractions were taken out

from the collection flask at the desired temperature points. During the distillation process it was observed that at temperature range of 175-180^{0}C there was great turmoil in the distillation flask. This may be due to the falling of cold condensate on the flask walls falling into the hot TPO. To avoid overflow of the hot TPO the heating rate was reduced to 20 Watt once 170^{0}C was reached. The distillates were sent to labs for analysis. Based on those properties different usage of the distillates were found.

The distillate in diesel range was selected and blended with diesel in proportions (20%, 40% and 60%). These blends were used to run a single cylinder, 4 stroke, air cooled, DI diesel engine. The combustion, performance and emission parameters were recorded and compared to that of diesel. All data collected from the engine were stored in a computer in excel sheet. Graphs were drawn to study and analyze combustion, performance and emission parameters.

Chapter 5

Results and Discussions

RESULTS AND DISCUSSION

5.1 Fractionally Distilled TPO Phase 1.

In the phase 1 of the fractional distillation carried out three temperature range were chosen. They were

1. 190 - 210 ^{0}C
2. 210 - 230 ^{0}C
3. 230 - 250 ^{0}C

The temperature of 190 ^{0}C was chosen as the starting point for the distillation procedure based on the quantity of distillate collected below that temperature which was very less. A 20 ^{0}C range was selected to ensure sufficient amount of distillate was collected at each temperature range in a uniform manner. All illustrations of the distillates collected are shown in Figure 5.1. The fuel properties of the distillates are mentioned in Table 5.1. Two things were observed

- The colour progressively darkened as temperature range at which they were collected increased. This was due to change in composition of the distillate based on boiling point.
- As time passed the colour of distillate changed from yellowish to brownish.

Table 5.1 Properties of Distilled TPO at different Temperature Ranges

Properties	**190-210^{0}C**	**210-230 ^{0}C**	**230 – 250 ^{0}C**
Density (kg/m^3 @20 ^{o} C)	830	856.6	900.2
Kinematic viscosity (cSt@40 ^{o} C)	0.83	1.12	1.41
Calorific value (MJ/kg)	40.8	41.35	41.46
Flash point by Abel method (^{o} C)	19	29	37
Fire point (^{o} C)	29	35	46
Cetane number	40-45	35-40	25-30
Sulphur Content (% w t)	Nil	Nil	Nil

Figure 5.1 Image of Fractionally Distilled Tyre Pyrolysis Oil

5.2 Fractionally Distilled TPO Phase 2

In the second phase of distillation was carried out basing the temperature on crude oil ranges. The temperature ranges chosen were:

1. 140 – 200 ^{0}C (Kerosene Range)
2. 200 – 270 ^{0}C (Diesel Range)
3. >270 ^{0}C (Lubricating Oil)

The distilled TPO at these ranges is shown in Figure 5.2. The properties are given in Table 5.2.

Table 5.2 Properties of TPO distillates

Properties	**Diesel**	**LFPO**	**TPO>270^{0}C**
Density (kg/m^3 @20 ^{o}C)	830	843.6	1046.3
Kinematic viscosity (cSt@40 ^{o}C)	2-4	0.84	15.88
Calorific value (MJ/kg)	43.8	41.5	-
Flash point by Abel method (^{o}C)	50	29	75
Fire point (^{o}C)	56	35	95
Cetane number	45-50	35-40	-
Sulphur Content (% w t)	0.29	Nil	4.00
Neutralization Value(mg of KOH)	-	-	1.11
Pour Point (^{0}C)	-	-	-15
Copper strip corrosiveness at 40^{0}C for 3 hrs			Negative

(a) **(b)**

Figure 5.2 (a) Distillate 200-270 ^{0}C (b) Distillate> 270^{0}C

5.3 Results from Engine run with LFPO blends

5.3.1 Combustion Parameters

5.3.1.1 Cylinder Pressure vs Crank Angle

Figure 5.3 indicates the variation of the cylinder pressure with respect to the crank angle for diesel, 20LFPO, 40LFPO and 60LFPO at full load condition.

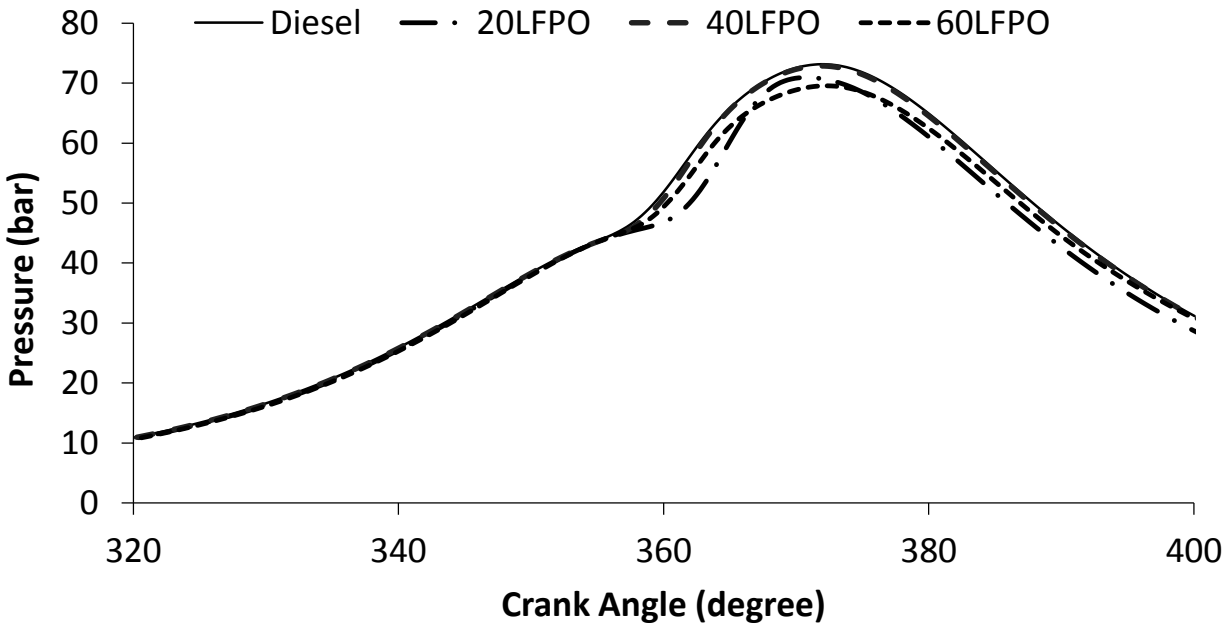

Figure 5.3 Cylinder Pressure vs Crank Angle

The start of fuel injection (SOI) is set at 23^0 bTDC. It is observed from the figure 5.3, that the combustion starts later by about 0.423^0CA, 0.36^0CA and 0.42^0CA for 20LFPO, 40LFPO and 60LFPO respectively, compared to that of diesel at full load. Combustion starts later for LFPO-diesel blends may be due to poor ignition quality and higher density of LFPO-diesel bends.

This is one of the most important graphs for combustion analysis. The pressure inside the cylinder depends on factors like: combustion, heat transfer rate, crevice region, instantaneous cylinder volume and leakage. The significance of this graph, also known as the p-θ diagram, are as follows:

- It indicates the process occurring near the TDC clearly.
- Gives information about instantaneous pressure at each crank angle degree.
- Gives the peak cylinder pressure, rate of pressure rise and maximum rate of pressure rise.
- Quantitatively defines the combustion process.
- Heat release rate, ignition delay, combustion duration, mass fraction burnt and gas condition for pollutant formation can be inferred from this diagram.

5.3.1.2 Cylinder Peak Pressure

Figure 5.4 shows the variation of the cylinder peak pressure at different values of brake power.

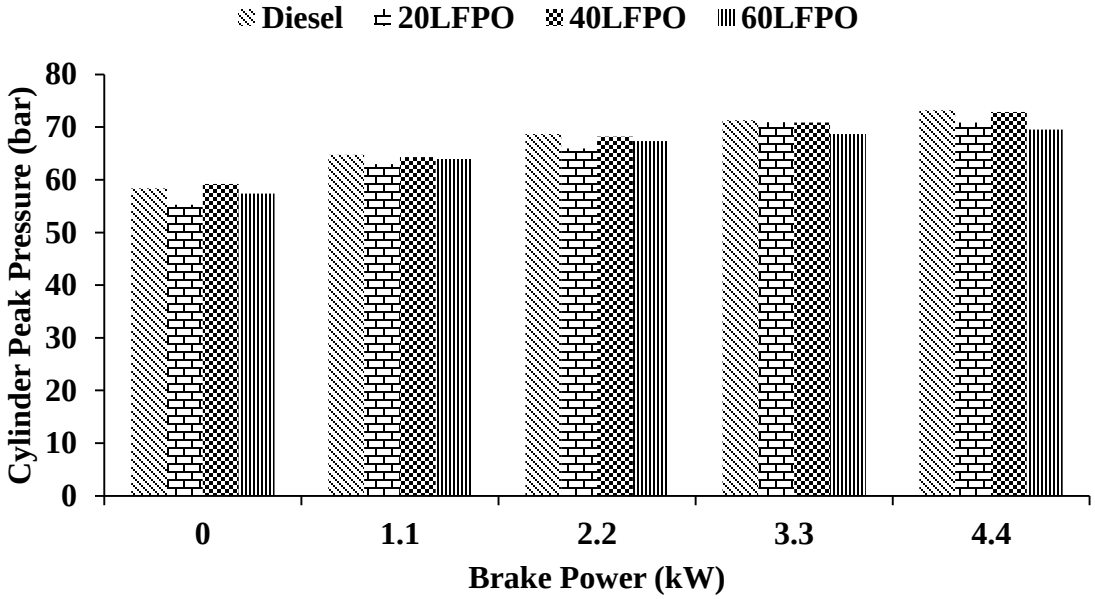

Figure 5.4. Cylinder Peak Pressure vs Brake Power

The cylinder peak pressure increases with increasing the load. The cylinder peak pressure of diesel, 20LFPO, 40LFPO and 60LFPO are found to be about 73.17, 70.86, 72.87 and 69.55 bar at full load respectively. The cylinder peak pressure of diesel is the highest compared to all the blends and 40LFPO shows a higher value of cylinder pressure among the LFPO diesel blends. The peak cylinder pressure of all the LFPO diesel blends are lower because of lower heat release inside the cylinder.

5.3.1.3 Heat Release Rate

Figure 5.5 illustrates the heat release rate pattern with the crank angle at full load. The heat release rate was calculated using the first law analysis of the pressure crank angle data. The heat release rate at each crank angle was calculated by using the expression given below:

$$\dot{Q} = \frac{\gamma}{\gamma-1} p \frac{dV}{d\theta} + \frac{1}{\gamma-1} V \frac{dp}{d\theta} \quad (5.1)$$

Where the apparent heat releases (J), γ is is the ratio of specific heats, P is the instantaneous cylinder pressure (N/m^2), and V is instantaneous cylinder volume (m^3) . The amount of heat release in the premixed combustion of a CI engine depends on the ignition.

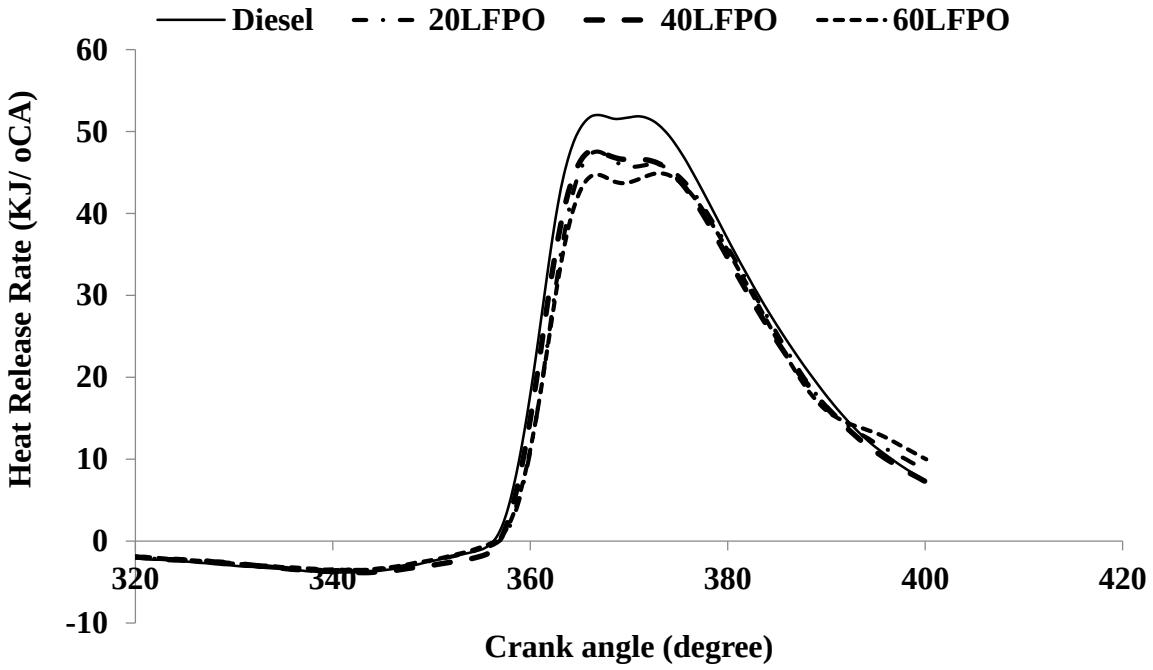

Figure 5.5 Heat Release Rate vs Crank Angle

5.3.1.4 Combustion Duration

Figure 5.5 illustrates the variation of maximum heat release rate with brake power. Initially the maximum heat release is increase than decrease at full load. The maximum heat release rate is found to be the highest with diesel in this study, which is 47.99 J/ ^{0}CA. Among all the LFPO shows the lowest maximum heat release rate at full load.

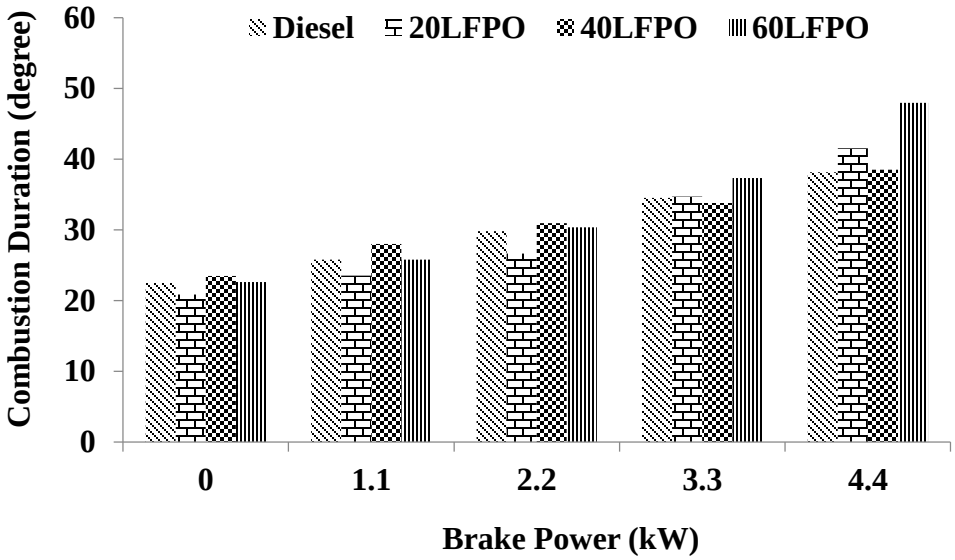

Figure 5.6 Combustion Duration vs Brake Power

As the percentage of LFPO increases in the blends, the maximum heat release rate decreases, as a results of poor mixture formation. Figure 5.6 shows the variation of the combustion duration with brake power. It can be observed from the figure that, the combustion duration increases with increase in the brake power for all the tested fuels, which may be due to the increase in the quantity of fuel injected.

It is also observed from the figure, that the combustion duration is higher for all the blends compared to that of diesel operation. Increasing the LFPO percentage in the diesel blends, results in a longer combustion duration. This may be due to the high boiling point compounds present in the LFPO, and its lower cetane number, which takes more time for the chemical reaction At full load, the value of the combustion duration for diesel is found to be about 38.127 J/ ^{o} C A, and for 20LFPO, 40 LFPO, 60 LFPO the values are about 41.52809, 38.50267 and 47.9282 J/ ^{o} C A respectively.

5.3.2 Performance Parameters

5.3.2.1 Brake specific Energy Consumption vs Brake Power

BSEC is a reliable parameter, when two fuels with different density and heating value are blended together and used in an engine. Fig. 5.7 shows the variation of BSEC for diesel and LFPO blends, with respect to brake power.

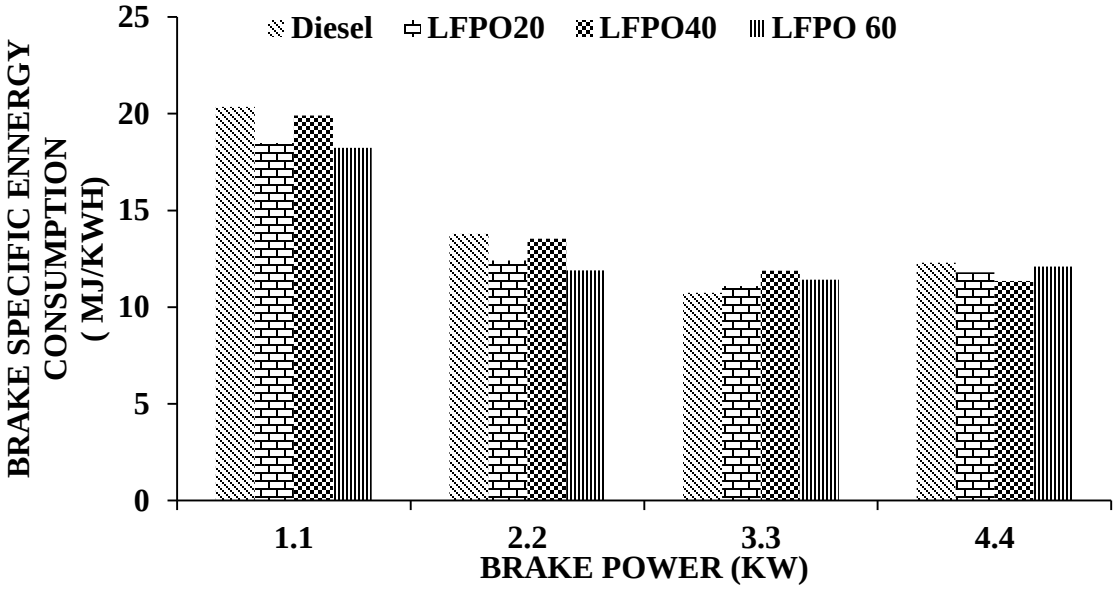

Figure 5.7 Brake specific Energy Consumption vs Brake Power

The BSEC for diesel is 12.29 MJ/kWh at full load and it is approximately 11.8, 11.35 and 12.1 MJ/kWh for LFPO20, LFPO40 and LFPO60 diesel blends respectively. As the load increases the BSEC decreases for diesel, and all the LFPO diesel blends, because of increase in cylinder temperature. The BSEC for diesel is found to be the lowest among all the fuels tested in this study. This is attributed to a better and complete combustion and higher heating value than these of LFPO blends. The engine consumes more fuel with the LFPO diesel blends than that of diesel to develop the same power output. This is because of lower heating value and higher density of the blends. The BSEC is the lowest for LFPO40 11.35 MJ/kWh due to better combustion and Cetane values.

5.3.3 Emission Parameters

5.3.3.1 NOx Emission

The parameter affecting formations of NOx in a CI engine are the combustion duration, temperature, higher compression ratio, pressure and the availability of oxygen. Figure. 5.8 depicts the variation of NO emission with brake power for diesel and the LFPO diesel blends.

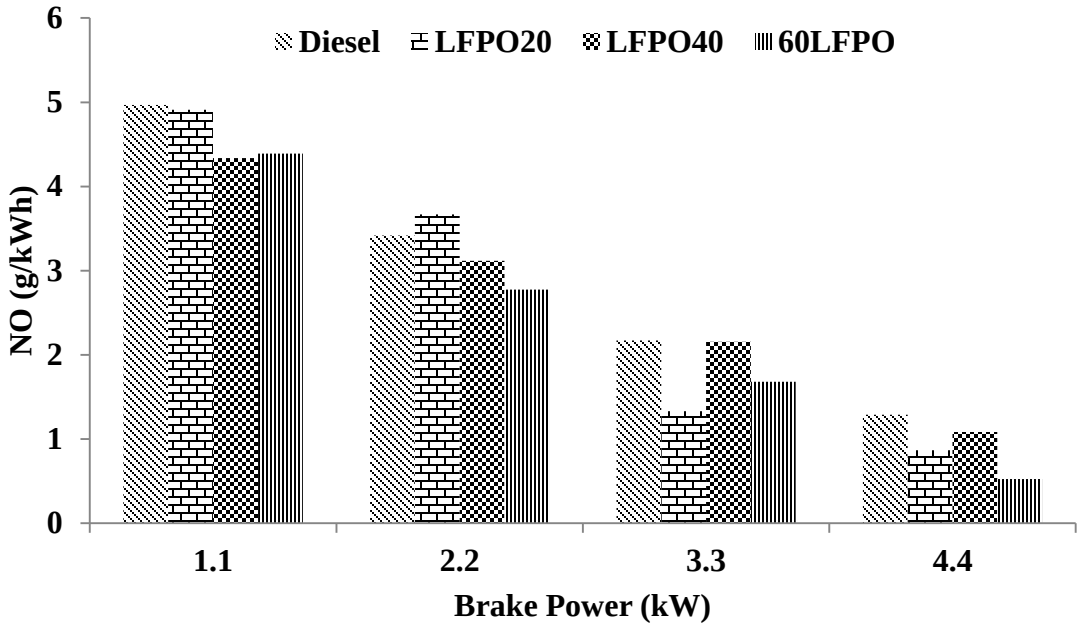

Figure 5.8 NO emission vs Brake Power

The NO emission per kWh for diesel and all the LFPO diesel blends decrease as the load increases. The value of NO emission is found to be the highest for diesel at full load among all the fuels tested in this study. This may be due to higher heating value and complete combustion than the all given blends. The value of NO emission higher for diesel is 1.290 g/kWh at full load. While increasing the LFPO percentage, the NO emission decreases.

5.3.3.2 Smoke Opacity

Smoke occurs due to the incomplete combustion inside the combustion chamber, and normally formed in the rich zone. Figure.5.9. illustrates the smoke emission measured in the engine exhaust, for the fuels tested in this study.

With the increase in load, the air fuel ratio decreases as the amount of fuel injected increases, and hence results in higher smoke. The smoke emission for diesel is found to be the lowest at full load among all the fuels in this study. The LFPO has high density and viscosity, so high smoke emission

is recorded. The values of smoke emission for diesel, LFPO20, LFPO40 and LFPO60 are 61.2%, 82.2%, 69.2 % and 95% respectively, at full load operation.

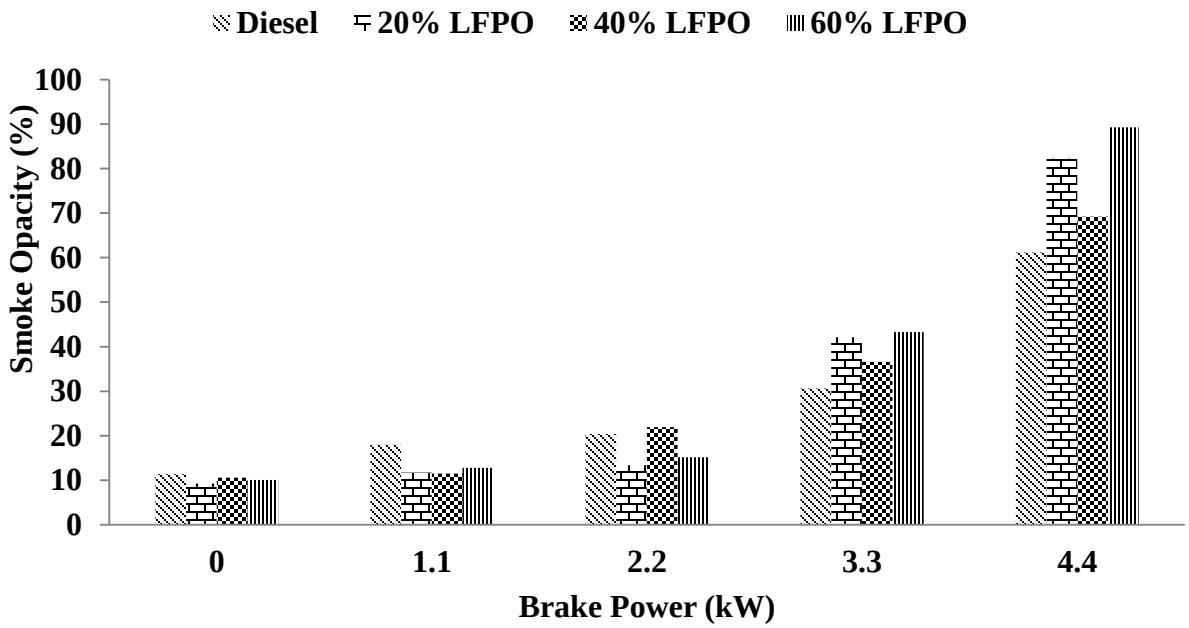

Figure 5.9 Smoke Opacity vs Brake Power

5.4 Discussion on Combustion of 40LFPO

As the aromatic content of a fuel increases its cetane number decreases. The combustion is delayed and we get a decrease in performance and increase in emission. The building block of aromatic hydrocarbon is the benzene (C_6H_6) ring structure. The structure is very stable and accommodates additional $–CH_2$ groups in side chains and not by ring expansion. Example: Toluene (one CH_2 group added to the benzene ring C_7H_8).

The working fluid in engine are gas mixtures in which fuel is injected. The fuel vaporizes in a phase called the physical phase. Then the chemical reaction starts just before combustion, known as the chemical phase. Both these phases constitute the ignition delay period. Depending on the problem under consideration and the portion of the engine cycle in which it occurs, chemical reaction may:

1. Be so slow that they have a negligible effect on mixture composition (the mixture composition is essentially frozen)
2. Be so rapid that the mixture state changes and the composition remains in chemical equilibrium.
3. Be one of the rate controlling processes that determine how the composition of the mixture changes with time.

There is a special case when the aromatic content of a fuel can increase the Cetane number. It happens when an aromatic ring is connected to a long chain alkyl group. The reaction of this alkyl group provides sufficient energy to break the aromatic ring releasing large amount of energy. The increase in the aromatic content with increase in proportion of LFPO the kinetics of reaction favors alkyl aromatics formation for 40LFPO and 60LFPO and gives rise to the following situations:

- At low fraction (20LFPO) blends Cetane number remains constant with increase in aromatic content.
- At medium fraction (40LFPO) blends Cetane number is improved due to condensation of aromatics with long chained alkanes.
- At higher fraction (60 LFPO) blends Cetane number decreases along with increase in aromatic content.

Thus in 40LFPO we get better performance and emissions compared to 20LFPO and 60LFPO blends.

5.5 Discussion on 40LFPO as a fuel

Based on combustion, performance and emission characteristics of the three blends of LFPO (20, 40 and 60) it was found that 40LFPO gave the best results. All data obtained for 40LFPO were close to that of diesel. It satisfies the emission standards required. Thus it is a new blend of fuel that can be used to run a DI diesel Engine.

5.6 Discussion on TPO distillate collected <270^{0}C

Properties like pour point, neutralization point, flash point, corrosiveness and Kinematic viscosity were checked to find out if it can be used as base oil for manufacture of lubricants. The distillate is non corrosive and has high kinematic viscosity. A low pour point of -15^{0}C ensures that it can flow at very low temperatures also. All these properties correspond to the properties of base oil used for lubricants. The down side of this oil being used as base oil rest on the fact that it has high aromatic content which is undesirable.

CONCLUSION

The results obtained show the high potential of tyre pyrolysis oil of being used in various fields. The different grades of oil obtained after distillation increases its commercial value. But the focus of this report is on its environmental impact. Although some TPO plants have come up, only 20 – 25% of scrap tyres are being recycled by this process. Making the production of TPO more lucrative, will result in more percentage of scrap tyres recycled in this manner. As a result scrap tyres won't be disposed of into the environment in form of landfills or wastes; rather they will be properly processed and converted to useful products. The fact that pyrolysis of waste tyres is considered to be a useful solution to protect the environment, it can also be made cost-effective.

Fractionating the TPO by distillation is a very important procedure that is often overlooked. If TPO is directly used as a fuel, the presence of PAHs and aromatic compounds release many harmful anthropogenic gases into the atmosphere. The sulfur content present in it means that it is almost impossible for the fuel to pass stringent emission standards when used in IC engines in future. By distilling it we obtain a very clean fuel which is completely free from sulfur and PAHs. Lubricants don't undergo combustion and seldom come to direct human exposure. So the risk of releasing harmful toxic gases is greatly reduced compared to all other methods of disposing scrap tyres. Thus the remains of the distillation can be used to manufacture low grade lubricants.

There were some new findings related to the combustion of TPO and the anomalous results its blends with diesel fuel give. Theoretical studies on combustion helped immensely to solve this problem. Formation of alkyl aromatics during combustion improves combustion due to which 40LFPO gives better combustion and emission characteristics compared to other fuel blends.

Future Work

The basic work done in fractionating the TPO,

- Improving the fuel created – 40 LFPO.
- Using the liquid fractions and gases collected in the kerosene range to power up stoves and lights.
- Manufacturing a Lubricating Oil from TPO as feedstock.
- Modifying Engine Parameters to match the properties of 40 LFPO.

REFERENCES

[1] "Wikipedia," [Online]. Available: http://en.wikipedia.org/wiki/EPA

[2] P. M. Bhatt and P. D. Patel, "Suitability of Tyre Pyrolysis Oil as an Alternative Fuel for Internal Combustion Engine," *International Journal of Advanced Engineering Research and Studies,* vol. 1, no. 4, pp. 61-65, 2012.

[3] M. Murena, E. Garufi, R. B. Smith and F. Gioia, "Hydrogenative Pyrolysis of Waste Tires," *Journal of Hazardous Material,* vol. 50, pp. 79-98, 1996.

[4] M. R. Islam, M. Praveen and H. Hanui, "Innovation in Pyrolysis Technology for Management of Scrap Tire: A Solution of Energy and Environment," *Internationa Journal of Environmental Science and Development,* vol. 1, pp. 264-271, 2010.

[5] I. Cumali and A. Huseyin, "Fuel Production from Waste Vehicle Tires by Catalytic Pyrolysis and its Application in a Diesel Engine," *Fuel Processing Technology,* vol. 92, pp. 1129-1135, 2011.

[6] P. T. williams, B. P. Bottrill and A. M. Cunliffe, "Combustion of Tyre Pyrolysis Oil," *Institution of Chemical Engineers,* vol. 76, pp. 957-963, 1998.

[7] A. Sharma and S. Murugan, "Investigation on the behaviour of a DI Diesel Engine Fueled with Jatropha Methyl Ester (JME) and Tyre Pyrolysis Oil (TPO) blends," *Fuel,* vol. 108, pp. 699-708, 2013.

[8] S. Murugan, M. C. Ramaswamy and G. Nagarajan, "Performance, Emission and Combustion studies of a DI Diesel Engine using Distilled Tyre Pyrolysis Oil-Diesel Blends," *Fuel Processing Technology,* vol. 89, pp. 152-159, 2008.

[9] Heywood, Internal Combustion Engine Fundamenta's, New Delhi: McGraw Hill Education, 2013.

[10] Y. Kidoguchi, C. Yang and R. Kato, "E!ects of Fuel Cetane Number and Aromatics on Combustion Process and Emissions of a direct-injection Diesel Engine," *Society of Automotive Engineers,* vol. 21, pp. 469-475, 2000.

[11] "Wikipedia," [Online]. Available: http://en.wikipedia.org/wiki/Pyrolysis.

[12] A. I. Rushdi, A. Y. BaZeyad, A. S. Al-Awadi and K. F. Al-Mutlaq, "Chemical Characteristics of Oil-like Products from Hydrous Pyrolysis of Scrap Tires at Temperatures 150-400," *Fuel,* pp. 578-584, 2013.